HARNESSING HAVOK AND MACHINE LEARNING FOR COSMIC RAY FORECASTING

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Abstract. *This research explores an innovative approach to forecasting cosmic ray activity by integrating the HAVOK model with machine learning algorithms. The study uses data from the Tbilisi Cosmic Rays Observatory, spanning from 2012 to 2020. The focus is on analyzing chaotic systems, including the Lorenz and Mackey-Glass models, to validate the HAVOK-ML method for predicting cosmic ray flux. The results demonstrate the method's potential to enhance space weather forecasts, with broader applications in predicting solar activity, supernovae, gamma-ray bursts, and air quality monitoring. The model is implemented using Python, Julia, and machine learning frameworks like Keras.*

Keywords: *HAVOK model, Space weather, Lorenz system, Mackey-Glass system, Chaos theory, Time series prediction, Air quality, Solar activity, Supernovae, Python, Julia, Keras.*

Introduction

Cosmic rays, high-energy atomic nuclei that travel through space at nearly the speed of light, provide crucial insights into various cosmic phenomena such as supermassive black holes, exploding stars, and the chemical and physical makeup of the universe. These rays, predominantly originating from supernova explosions, interact with Earth's atmosphere, creating secondary particles that can be detected and analyzed. Understanding and predicting the behavior of cosmic rays is essential for advancing our knowledge of space weather and its impact on technology and communications. This research aims to improve cosmic ray activity forecasts by combining the HAVOK model with machine learning algorithms. The HAVOK model is a data-driven method that decomposes complex time series data into simpler, interpretable components, while machine learning learns from historical data, identifies patterns, and improves forecast accuracy. Together, these approaches provide a powerful tool for analyzing chaotic systems and enhancing the prediction of cosmic ray behavior. The HAVOK-ML method employs the Singular Value Decomposition (SVD) of Hankel matrices to identify dominant modes within a system, constructing a low-dimensional model that simplifies the analysis of future states. By applying this method to well-known chaotic systems such as the Lorenz system, the study demonstrates its effectiveness in predicting cosmic ray activity. The data used in this research, sourced from the Tbilisi Cosmic Rays Observatory, spans from 2012 to 2020 and includes cosmic ray interactions captured by a 9-channel detector. These data, combined with advanced programming techniques using Python, Julia, and machine learning frameworks such as Keras, are instrumental in the implementation of the HAVOK-ML method

The purpose of task

The purpose of this research is to develop an enhanced method for predicting cosmic ray activity by combining the HAVOK model with machine learning algorithms. This approach aims to improve the accuracy of forecasts related to space weather phenomena, particularly the impact of cosmic ray flux on Earth's magnetic field and atmosphere. As cosmic rays interact with Earth's magnetic field, they are often deflected, though higher-energy cosmic rays can penetrate near the magnetic poles, particularly during periods of geomagnetic storms caused by solar flares and coronal mass ejections (CMEs). Understanding these interactions is crucial, as fluctuations in Earth's magnetic field over time can influence cosmic ray penetration, impacting atmospheric chemistry, cloud formation, and climate. By analyzing chaotic systems and utilizing data from the Tbilisi Cosmic Rays Observatory, this study seeks to demonstrate the effectiveness of the HAVOK-ML method, with broader applications in predicting solar activity, supernovae, geomagnetic field reversals, and their effects on space weather and air quality

Results

Our results demonstrate the successful application of the HAVOK-ML method on both the Lorenz and Mackey-Glass time series. The predictions generated by our model align closely with the actual data, indicating the effectiveness of this hybrid approach in predicting chaotic systems. The code for this process was developed in Python, incorporating functions with parameters tailored for each system, including the Lorenz and Mackey-Glass systems.

1. **Lorenz System Training Data:** The first figure shows the training data for the Lorenz system, with variables x, y, and z represented in different colors. The model was trained on this data to predict the system's future states. The consistency between the original and predicted data underscores the accuracy of the HAVOK-ML method.
2. **Mackey-Glass Chaotic Series Training Data:** The second figure illustrates the training data for the Mackey-Glass chaotic series. This system is widely used for testing predictions in nonlinear and chaotic systems. The HAVOK-ML method, trained on this data, successfully captured the behavior of the system, as evidenced by the alignment between predictions and actual data.
3. **Cosmic Ray Training Data:** The third figure presents the cosmic ray training data, which consists of both uncorrected and corrected cosmic ray counts. This data, collected from the Tbilisi Cosmic Rays Observatory, was used to further tailor the model for predicting cosmic ray activity. By using real-world cosmic ray data from 2012 to 2020, we ensured that our predictions were grounded in observed phenomena.
4. **HAVOK-ML Prediction of Lorenz Time Series using Cosmic Rays:** The final figure showcases the prediction of the Lorenz time series using cosmic ray data as the training set. The orange line represents the predicted data, which aligns closely with the original data, illustrating the model's accuracy in handling complex and chaotic time series like the Lorenz system, when trained on real-world cosmic ray observations.

These results highlight the robust predictive capabilities of the HAVOK-ML method, with extensive applications in forecasting cosmic ray flux. The model's accuracy in predicting chaotic systems has broad implications for space weather forecasting, including predicting the effects of cosmic rays on satellites, astronauts, and communication systems, as well as solar activity and air quality monitoring.

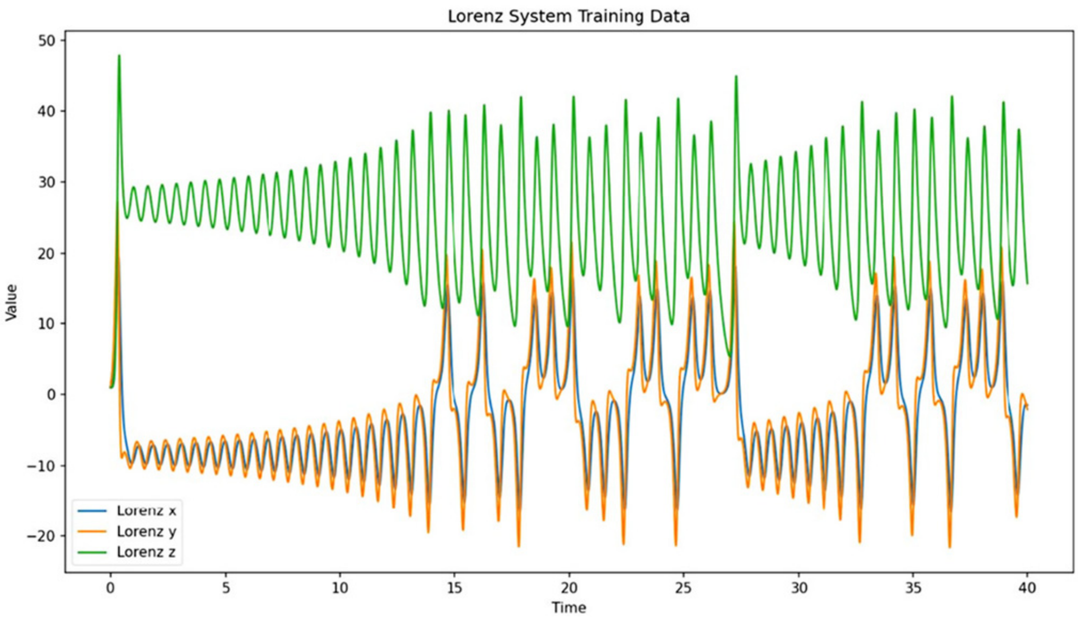

Figure 1.

Figure 1. The first figure, labeled **“Lorenz System Training Data”**, shows the time series of the Lorenz system's three variables: **x** (blue), **y** (orange), and **z** (green). These variables represent the three-dimensional state space of the Lorenz attractor, a well-known chaotic system often used in studies of nonlinear dynamics and chaos theory. The graph shows how the Lorenz system exhibits deterministic chaos, where small differences in initial conditions lead to vastly different trajectories over time. The training data from this chaotic system is used to predict future states of the system through the HAVOK-ML method. The close interaction of the three variables highlights the complex nature of the Lorenz system, making it an ideal candidate for testing the predictive power of the model

The purpose of the research

The purpose of this research is to develop an enhanced method for predicting cosmic ray activity by combining the HAVOK model with machine learning algorithms. This approach aims to improve the accuracy of forecasts related to space weather phenomena, particularly the impact of cosmic ray flux on Earth’s magnetic field and atmosphere. Understanding these interactions is crucial, as cosmic rays interact with Earth’s magnetic field, are deflected, and have varying degrees of penetration based on their energy and solar activity. By analyzing chaotic systems and utilizing data from the Tbilisi Cosmic Rays Observatory, this study seeks to demonstrate the effectiveness of the HAVOK-ML method, with broader applications in predicting solar activity, supernovae, geomagnetic field reversals, and their effects on space weather and air quality. The data used in this research is sourced from the Tbilisi Cosmic Rays Laboratory, which collects cosmic ray information using a 9-channel detector system. The information gathered is processed through connected devices and uploaded to global servers for further analysis. The current equipment is undergoing modernization, where traditional electronics will be replaced with advanced microprocessors. Once fully upgraded, these new systems will autonomously process data and automatically upload it to global servers, offering real-time insights. This advanced setup ensures that the predictions are based on accurate and up-to-date cosmic ray data. The combination of the HAVOK model with machine learning leverages this data to improve forecast accuracy, enabling predictions of cosmic ray activity with applications in space weather, satellite safety, communication systems, and even air quality monitoring. The ultimate goal is to create a predictive framework that helps mitigate the effects of cosmic rays on Earth’s technological and environmental systems.

Fig. 1. Existing electronics, a detector with 9 channels, from which information is sent to the computer

Fig 2. Raspberry pi

Electronics and software that are in the process of being updated give us a number of simplification results. In autonomous mode, it will be possible to build graphs, upload to a global server, remote access from any place and most importantly, it allows for future updates both in terms of software and electricity.

Summary

Cosmic rays, originating from cosmic events, influence Earth’s climate by ionizing the atmosphere and creating cloud condensation nuclei (CCN), which affect cloud formation and temperature. These interactions are further influenced by fluctuations in the Earth's geomagnetic field, which can modulate cosmic ray intensity and impact the climate over decadal timescales. Understanding the complex relationship between cosmic rays, the geomagnetic field, and climate is crucial and requires more advanced research. To support this research, the Tbilisi Cosmic Ray Laboratory is undergoing significant hardware and software upgrades. These improvements will enable more accurate and autonomous data processing of cosmic ray activity, facilitate transmission to global servers, and provide remote access for future studies. By upgrading the laboratory’s technology, researchers aim to better analyze the interactions between cosmic rays, Earth's magnetic field, and climate. This research seeks to develop and refine a predictive model for cosmic ray activity by combining the HAVOK model with machine learning algorithms. The hybrid approach will enhance the understanding of space weather phenomena and improve the accuracy of forecasting cosmic ray flux. By applying this method to chaotic systems and utilizing data from the Tbilisi Cosmic Rays Observatory, the study aims to demonstrate the HAVOK-ML method's practical applications in mitigating the effects of space weather on satellites, communication systems, and air quality monitoring.

Referenses

[1] Data from the Tbilisi Cosmic Ray Laboratory.

[2] A Hybrid Method Using HAVOK Analysis and Machine Learning for Predicting Chaotic Time Series